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Review of methods for the calculation of cell temperature in high concentration photovoltaic modules for electrical characterization

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ABSTRACT

The solar cell operation temperature is an important input in models for the electrical characterization of high concentration photovoltaic cells and modules. However, the direct measurement of this temperature is difficult in these kinds of devices. Because of this, in recent years, the scientific community has proposed different methods for indirectly calculating the cell temperature in high concentration photovoltaic modules from atmospheric parameters and/or easily measurable parameters on the module. In this paper, a comprehensive review of existing methods for cell temperature calculation in high concentration photovoltaic modules for electrical characterization is presented. The different methods are summarized and a comparative analysis is done. Required inputs, advantages and technical difficulties of each method are highlighted. Also, an experimental campaign has been carried out at Jaén, south of Spain, in order to quantify the accuracy of the methods. Results show that methods based on direct measurements on the module are somewhat more accurate than methods only based on atmospheric parameters. The choice of the most suitable method for a specific application will depend on the availability of module information, on the required accuracy and on technical issues.

Contents

Abbreviations: HCPV, high concentration photovoltaic; MPP, maximum power point; RMSE, root mean square error; ANN, artificial neural network

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1. Introduction

High concentration photovoltaic (HCPV) systems use optical devices (lenses or mirrors) to concentrate the sunlight onto small solar cells. Although there are a lot of possible configurations in order to implement this concept [1,2], a typical HCPV system consists of a two-axis solar tracker on which HCPV modules are mounted, each module composed of several electrically connected solar cells with their associated optics. The small size of the solar cells allows incorporating high efficiency III–V multi-junction solar cells, while other silicon-based solar cells can also be used [3]. One of the advantages of these systems is the high potential of costs reduction because they replace expensive semiconductor materials by cheaper optical materials [4]. As well, the operation with high efficiencies implies an increase of produced energy for the same installed area than a conventional photovoltaic system [5].

The operation temperature of the cells in an HCPV module affects its performance. This is because the band-gap of the semiconductors that compose the solar cells reduces when temperature increases. This implies a change in the solar cells electrical parameters: open-circuit voltage, fill factor, maximum power and efficiency decrease with increasing temperature, while short-circuit current increases (Fig. 1). These effects have been observed for both silicon-based solar cells and III–V multi-junction solar cells [6–9]. As HCPV modules behavior is influenced by the cells inside, HCPV modules electrical parameters are affected by temperature in the same way [10,11]. Thus, knowledge of the cell temperature is critical for characterizing the behavior of HCPV modules.

While cell temperature is an important input in models for the electrical characterization of HCPV cells and modules [12], the direct measurement of this temperature in HCPV modules seems to be difficult because it requires accessing inside the module and placing of a small temperature sensor very close to the solar cell [13]. Although in conventional flat-plate modules the cell temperature can be adequately estimated by measuring the temperature on the back of the module, in HCPV modules the complex thermal behavior and the use of heat exchangers for keeping the cell temperature in acceptable levels and avoiding degradation make difficult this practice [14,15]. Because of these difficulties, in recent years the scientific community has devoted efforts in developing methods for indirectly calculating the cell temperature in HCPV modules from different parameters (atmospheric parameters and/or easily measurable parameters on the module).

The cell temperature is not only important in the modeling of HCPV modules, but it has interest in the power rating of these devices. Conventional photovoltaic modules are rated at specific conditions of cell temperature, usually at 25 °C of cell temperature [16]. In contrast, HCPV modules are usually rated at defined conditions of environmental parameters due to the difficulty of measuring the cell temperature. For instance, the ASTM standard E2527-06 [17] requires ambient temperature of 20 °C, direct normal irradiance of 850 W/m^2 and wind speed of 4 m/s. Although establishing these conditions avoids the need of measuring cell temperature, the obtained rated maximum power is not directly comparable to that obtained for other photovoltaic technologies. This is an issue for market penetration of HCPV technology [18]. Thus, it would be desirable to have rating procedures based on standard cell temperature conditions [19] and methods that reliably calculate cell temperature.

In this paper, a comprehensive review of existing methods for calculating cell temperature in HCPV modules for electrical characterization is presented. Its aim is to help the photovoltaic researchers and professionals in the choice of the most suitable method for each application. The review comprises all the relevant contributions in this field, mainly developed in the last 3–4 years. Two remarks must be done:

There are a lot of methods for calculating the cell temperature in conventional flat-plate modules [20]. Among these methods, only methods that have been applied for HCPV modules are included in the present review.

In recent years, network thermal models have been proposed that predict temperature distributions across the module [21–25]. These models are oriented to thermal management and module design studies. As their implementation is complex, they are not intended for electrical characterization, so that they will not be included in the present review.

Taking this into account, the reviewed methods have been grouped according to the following classification: on the one hand, methods based on direct measurements on the module; on the other hand, methods based on atmospheric parameters. Furthermore, methods based on direct measurements have been divided into methods based on module heat-sink temperature and methods based on electrical parameters (Fig. 2). Methods based on direct measurements are expected to be more accurate than methods based on atmospheric parameters, while methods based on atmospheric parameters present the advantage that the cell temperature can be estimated at any location from meteorological data.

The paper is organized as follows: Section 2 is an overview of HCPV technologies; Sections 3, 4 and 5 summarize the methods for cell temperature calculation in HCPV modules according to the proposed classification: methods based on module heat-sink temperature (Section 3), methods based on electrical parameters (Section 4) and methods based on atmospheric parameters (Section 5); a comparative analysis of the methods from both a qualitative and a quantitative point of view is done in Section 6; finally, Section 7 presents the conclusions of the work.

It is important to remark that not every cell in an HCPV module exactly operates at the same temperature. Measurements on the back plates of HCPV modules have shown that cells near the frame have lower temperatures depending on wind speed and direction and orientation of the module [26,27]. Because of this, authors use to work with the “average cell temperature” in the module. This parameter will be simply referred in this paper as the “cell temperature” of the module (T_c).

2. HCPV technology overview

HCPV systems operate under light concentrations between 300 and 2000 suns [5]. These systems can be built with the participation of different conventional industrial sectors, such as glass, steel, aluminum

Nomenclature

Acronyms

ANN	artificial neural network
ASTM	American Society for Testing and Materials
CEAEMA	Centro de Estudios Avanzados en Energía y Medio Ambiente
HCPV	high concentration photovoltaic
IEC	International Electrotechnical Commission
IES-UPM	Instituto de ENERGÍA Solar – Universidad Politécnica de Madrid
ISFOC	Instituto de Sistemas Fotovoltaicos de Concentración
MPP	maximum power point
NREL	National Renewable Energy Laboratory
PMMA	poly(methyl methacrylate)
PVUSA	photovoltaics for utility scale applications
RMSE	root mean square error

List of symbols

β_{Voc}	temperature coefficient of the open-circuit voltage (V/°C)
$\beta_{Voc,cell}$	temperature coefficient of the open-circuit voltage for a solar cell (V/°C)
$\beta_{Voc,cell}(X_c=1)$	temperature coefficient of the open-circuit voltage for a solar cell at one sun (V/°C)
β_{Voc0}	temperature coefficient of the open-circuit voltage at the reference irradiance (V/°C)
ΔT	temperature difference between the cell and the heat-sink at the reference irradiance (°C)
ΔT_{meas}	temperature difference between the cell at open-circuit and the ambient (°C)
ΔT_{MPP}	temperature difference between the cell at maximum power point and the ambient (°C)
η_{meas}	averaged electrical efficiency of an HCPV module while measuring an *I–V* curve (dimensionless)
η_{MPP}	electrical efficiency of an HCPV module working at maximum power point (dimensionless)
η_{opt}	optical efficiency (dimensionless)
λ	thermal conductivity of a material (W m^{-1}/°C)
ρ	internal thermal resistance of an HCPV module (°C/W m^{-2})
a_1, a_2, b_1, b_2	parameters of the method of Peharz (V, V, V/°C, V/°C)
A_1, A_2, A_3	parameters of the atmospheric method for heat-sink temperature calculation of PVUSA (dimensionless, °C/W m^{-2}, °C/m s^{-1})
A_{mod}	module aperture area (m^2)
B_1, B_2	parameters of the atmospheric method for heat-sink temperature calculation of Sandia (dimensionless, 1/m s^{-1})
c	parameter of the method of Hornung (dimensionless)
c_1, c_2, c_3	parameters of the method of Fernández (V/W m^{-2}, V/°C, V)
C_g	geometric concentration (dimensionless)
d_1, d_2	parameters of the method of Almonacid (°C/W m^{-2}, °C/m s^{-1})
DNI	direct normal irradiance (W/m^2)
DNI^*	reference direct normal irradiance (W/m^2)
I_{sc}	short-circuit current (A)
$I_{sc}{}^*$	short-circuit current at reference conditions (A)
k	Boltzmann constant (m^2 kg/s^2 K)
L	thickness of a material (m)
m	parameter of the method of Hornung (°C/W m^{-2})
n	effective diode ideality factor of an HCPV module (dimensionless)
n_{cell}	diode ideality factor of a solar cell (dimensionless)
N_s	number of cells in series of an HCPV module (dimensionless)
P	electrical power harvested by an HCPV module (W)
P_{abs}	luminous power absorbed by the cells in an HCPV module (W)
$P_{meas,AVG}$	averaged electrical power harvested by an HCPV module while measuring an *I–V* curve (W)
P_{MPP}	electrical power harvested by an HCPV module working at maximum power point (W)
q	electron charge (C)
Q	rate of heat transfer (W)
Q_{meas}	rate of heat transfer for a module at open-circuit (W)
Q_{MPP}	rate of heat transfer for a module working at maximum power point (W)
R	thermal resistance between the cell and the heat-sink (°C/W m^{-2})
R_{th}	absolute thermal resistance between the solar cells in a module and the ambient (°C/W)
T_{air}	ambient temperature (°C)
T_c	cell temperature (°C)
$T_{c(K)}$	absolute cell temperature (K)
$T_{c(K)}{}^*$	reference absolute cell temperature (K)
$T_{c,meas}$	cell temperature measured at open-circuit (°C)
$T_{c,MPP}$	cell temperature working at maximum power point (°C)
$T_{h\text{-}s}$	module heat-sink temperature (°C)
$T_{h\text{-}s,0}$	heat-sink temperature at shutter initiation (°C)
V_{oc}	open-circuit voltage (V)
$V_{oc}{}^*$	open-circuit voltage at reference conditions (V)
$V_{oc,max}$	maximum open-circuit voltage registered during a shuttering procedure (V)
WS	wind speed (m/s)
WS_0	parameter of the method of Hornung (m/s)
X_c	concentration ratio (dimensionless)

or mechanics, that allows displacing the manufacturing process from the pure semiconductor industry. This is beneficial for a fast growth of this technology and offers opportunities for costs reduction [28]. HCPV systems mainly combine the following elements.

2.1. Solar cells

The photovoltaic cells used in these systems are designed to extract more current per unit of area than conventional cells. Solar cell open-circuit voltage and fill factor grow with the incident luminous flux and, as a consequence, conversion efficiency increases the more sunlight is concentrated (until a limit given by the Ohmic losses). Silicon-based solar cells can be used in HCPV, but III–V semiconductors-based cells are more suitable for concentration because of the lower base electrical resistivity. Nowadays, advanced III–V multi-junction solar cells have demonstrated the highest efficiencies because of a broad use of the sunlight spectrum and many HCPV systems are based on these kinds of cells [29].

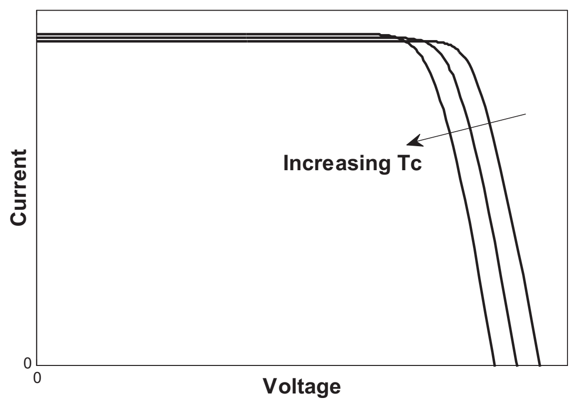

Fig. 1. Changes in the *I–V* characteristic curve of a solar cell when temperature increases.

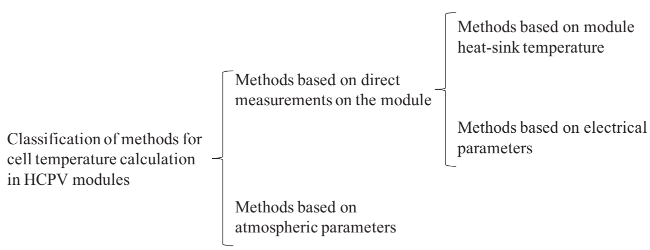

Fig. 2. Classification of the reviewed methods for the calculation of cell temperature in HCPV modules.

2.2. Optics

Lenses and/or mirrors are used to increase the luminous flux on the solar cells. Primary optics and secondary optics can be distinguished. Primary optics is intended for obtaining a high concentration level. Parabolic mirrors or Fresnel lenses are commonly used [30]. Secondary optics is optional. It receives the light from the primary concentrator and focuses it on the solar cell with the aim of light homogenization and angular acceptance improvement [31,32].

Several magnitudes related to the optics in HCPV are

The geometric concentration (C_g). It is the quotient between the primary concentrator area and the solar cell area.

The optical efficiency (η_{opt}). It is the quotient between the irradiation actually incident on the solar cell and the collected irradiation. As HCPV systems only exploit the direct component of sunlight, the collected irradiation is the product of the direct normal irradiance (*DNI*) by the primary concentrator area. η_{opt} accounts for the optical losses due to non-ideal properties of reflection, transmission and absorption of the optical elements.

The concentration ratio (X_c). It is the quotient between the mean irradiance actually incident on the solar cell and the one-sun irradiance (1000 W/m^2).

2.3. Solar receivers

A solar receiver is an assembly of one or several solar cells with the secondary optics and the mechanisms for current extraction and heat dissipation. It can incorporate other elements such as a bypass diode in order to prevent cell overheating in shading conditions (in two-axis trackers plants, modules on a tracker are shaded by the neighboring trackers at certain hours of the day) [33,34]. Fig. 3 shows the structure of a typical solar receiver integrated with a Fresnel lens-based primary optics. In this case, passive cooling is achieved by means of a finned heat exchanger. Some of the methods reviewed in this paper require measuring the heat-sink temperature ($T_{h\text{-}s}$) by placing a temperature sensor at the root of the heat exchanger behind the solar cell.

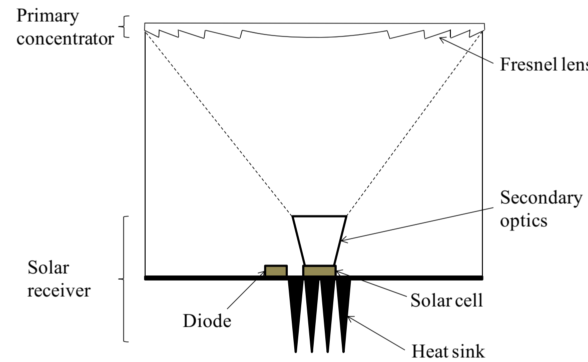

Fig. 3. Structure of a solar receiver integrated with Fresnel lens-based primary concentrator.

2.4. HCPV modules

An HCPV module is the smallest, complete, environmentally protected assembly of solar receivers and optical devices that is able to transform an input of unconcentrated solar radiation. Fig. 4 shows the main components and the structure of a typical HCPV module based on Fresnel lens parquets.

2.5. Tracking system

HCPV modules are mounted on a mobile structure in order to be always oriented to collect the solar rays. Some linear-focus systems can operate on single-axis solar trackers. However, two-axis trackers are the most used and are required for point-focus systems [35,36]. These trackers are more complex from a mechanical point of view but offer the advantage of higher light concentration. Solar trackers are composed of a tracking structure (structural elements and moving mechanisms) and the tracking control (electronic equipment that governs the motion). A set of modules mounted on the same tracker is known as a concentrator array, while a set of concentrator arrays connected to the same power output constitute an HCPV field [28].

3. Methods based on module heat-sink temperature

In this section, three methods for cell temperature calculation are summarized that require measuring the module heat-sink temperature ($T_{h\text{-}s}$). The heat-sink temperature is typically measured at the root of a finned heat exchanger (heat sink) on the back of the module. This temperature is distinctly different than the cell temperature in the case of HCPV modules and mainly depends on direct normal irradiance, position of the sensor, module design, ambient temperature, wind speed and direction and module electrical efficiency [26,37]. The direct measurement of the heat-sink temperature avoids using thermal models that try to estimate this temperature from atmospheric parameters but present uncertainty.

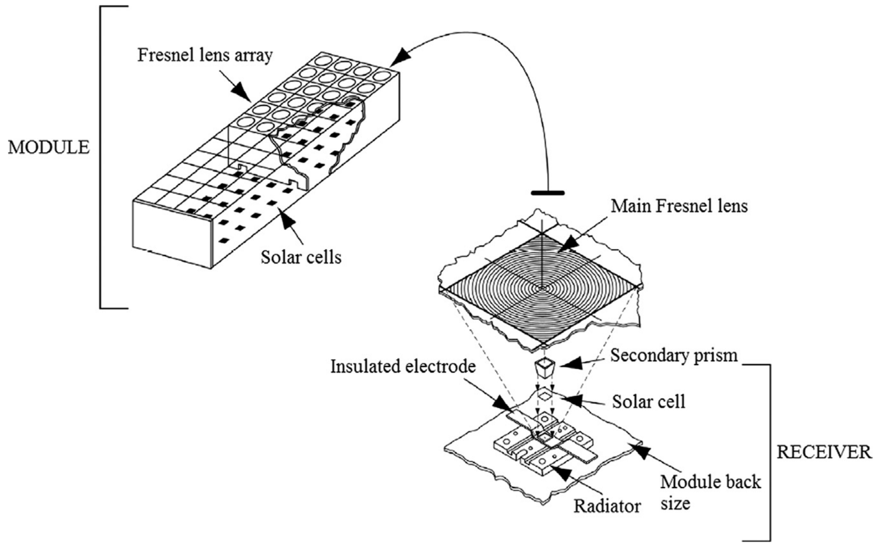

Fig. 4. Structure of an HCPV module based on point-focus Fresnel lenses.
Source: IEC 62108 [1].

3.1. Method of Sandia's photovoltaic array performance model (2004)

The method presented by King et al. [38] tries to express the cell temperature as a function of the heat-sink temperature and the *DNI*. For this purpose, it assumes one-dimensional thermal heat conduction through the module materials behind the cell. It is based on a simple equation as follows:

$$T_c = T_{h-s} + (DNI/DNI^*)\Delta T \quad (1)$$

ΔT being the temperature difference between the cell and the heat-sink at the defined reference direct normal irradiance DNI^*. Obtaining the ΔT parameter is not easy because it requires accessing inside the module in order to measure the cell temperature at the reference irradiance.

3.2. Method of ISFOC/IES-UPM (2008)

The method developed by the Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) in collaboration with the Instituto de Energía Solar of the Universidad Politécnica de Madrid (IES-UPM) [39] uses a similar assumption than the previous one, i.e. the relation between the cell and the heat-sink temperature is expressed as a function of *DNI*:

$$T_c = T_{h-s} + \rho DNI \quad (2)$$

The main difference with respect to the previous method is that the equation depends on a physical parameter, the so called "internal thermal resistance" (ρ, in °C/W m^{-2}), which is proportional to the thermal resistance, *R*, between the cell and the heat-sink. The ρ parameter can be theoretically calculated if the detailed structure of the materials behind the cell is known, as well as the geometric concentration ratio, C_g, and optical efficiency, η_{opt}, of the module. Proposed expressions for calculating ρ are [40]

$$R = \sum_i (L_i/\lambda_i) \quad (3)$$

$$\rho = \eta_{opt} C_g R \quad (4)$$

where index *i* represents each layer of material behind the cell, L_i and λ_i being the thickness and thermal conductivity of the material respectively. The theoretical calculation of ρ avoids the need of accessing inside the module; however, a detailed knowledge of the module design is required to perform this calculation and this information is not always available.

3.3. Method of Muller et al. (2011)

The method presented by Muller et al. [41] from the National Renewable Energy Laboratory (NREL) requires measuring both the heat-sink temperature and the open-circuit voltage. It has been included into this category of methods because it requires the heat-sink temperature, although it also could have been classified as a method based on electrical parameters. The method tries to overcome the limitations of common methods based on the open-circuit voltage, which are very sensitive to certain parameters not always easily obtainable, such as the effective diode ideality factor of the module.

One of the difficulties of this method is that it requires a system that shutters sunlight to the module while measuring the transients in open-circuit voltage. In order to get accurate results, a fast shutter must be available because the procedure is sensitive to the aperture time as well as a fast multimeter in order to be able to register the transients in open-circuit voltage. Also, the module must be covered for a significant period of time before all shuttering events in order to equilibrate the cell and heat-sink temperatures at the beginning of the procedure.

When the procedure is launched, the open-circuit voltage quickly grows until reaching a maximum ($V_{oc,max}$). Afterwards, it gradually decreases as the cell temperature increases until equilibrium is reached. The heat-sink temperature grows with time towards the equilibrium state and so does the cell temperature.

The following equation is proposed to model the behavior of the cell temperature during transient at an instant *t*:

$$T_c(t) = T_{h-s,0} + [V_{\text{oc, max}} - V_{oc}(t)]/\beta_{Voc} \quad (5)$$

$T_{h\text{-}s,0}$ being the measured heat-sink temperature at shutter initiation and β_{Voc} the temperature coefficient of V_{oc} for the module. The cell operating temperature can be obtained by evaluating this expression at an instant *t* in which the measured open-circuit voltage can be considered stable.

Authors of the method compared some results against manufacturers' suggestions and against a conventional method based on the open-circuit voltage. Results were in agreement for fast shutters. However, an experimental validation based on comparing against measured cell temperatures has not yet been reported.

4. Methods based on electrical parameters

In this section, the methods based on electrical parameters are summarized. These methods are based on the fact that the cell electrical parameters, specially the open-circuit voltage, vary with temperature. This allows estimating the cell temperature from the measurement of electrical parameters by using different procedures.

4.1. Method of the standard IEC 60904-5 (2011)

The method of the standard IEC 60904-5 [42] is known as the open-circuit voltage method. It requires measuring the module open-circuit voltage together with the incident *DNI*. The measured open-circuit voltage (V_{oc}) can be related with the open-circuit voltage at reference conditions ($V_{oc}{}^*$) as a function of absolute cell temperature ($T_{c(K)}$) and *DNI*

$$V_{oc} = V_{oc}{}^* + N_s(nkT_{c(K)}/q)\ln(DNI/DNI^*) + \beta_{Voc}(T_{c(K)} - T_{c(K)}{}^*) \tag{6}$$

N_s being the number of cells in series in the module, k the Boltzmann constant and q the electron charge. The defined reference conditions of irradiance and absolute cell temperature are denoted by DNI^* and $T_{c(K)}{}^*$ respectively. The expression also depends on two important parameters: the temperature coefficient of V_{oc} for the module (β_{Voc}) and the effective diode ideality factor of the module (n).

From this equation, the absolute cell temperature can be expressed as

$$T_{c(K)} = (V_{oc} - V_{oc}{}^* + \beta_{Voc}T_{c(K)}{}^*)/[N_s(nk/q)\ln(DNI/DNI^*) + \beta_{Voc}] \tag{7}$$

Expression that allows calculating the cell temperature as a function of V_{oc} and *DNI*.

While the β_{Voc} parameter is sometimes provided by the manufacturer, the n parameter is not easily obtainable. If these values are taken from the literature, there is the problem of uncertainty because the method is very sensitive to the chosen values.

A way of overcoming these problems is to carry out an outdoor experimental campaign in order to register measurements of cell temperature, open-circuit voltage and *DNI* over a significant period of time. For this purpose, a module with a cell temperature sensor must be available. From the collected data, a multi-linear regression analysis can be done taking into account Eq. (6) and a better estimate of the β_{Voc} and n parameters can be achieved [40].

An alternative to this method has been proposed by King et al. [38] that avoids the use of a pyrheliometer. It consists of approximating the DNI/DNI^* quotient by the relation between the measured short-circuit current (I_{sc}) and the short-circuit current at reference conditions ($I_{sc}{}^*$). This alternative is known as the "V_{oc}–I_{sc} method" [41,43] and thus, is based on the following equation:

$$T_{c(K)} = (V_{oc} - V_{oc}{}^* + \beta_{Voc}T_{c(K)}{}^*)/[N_s(nk/q)\ln(I_{sc}/I_{sc}{}^*) + \beta_{Voc}] \tag{8}$$

4.2. Method of Ju et al. (2013)

The method proposed by Ju et al. [43] can be regarded as an improvement of the V_{oc}–I_{sc} method, allowing the variation of the temperature coefficient of V_{oc} (β_{Voc}) with the irradiance level. Several authors have shown that the temperature coefficient of V_{oc} for a triple junction III–V solar cell ($\beta_{Voc,cell}$) can be expressed as a logarithmic function of the concentration ratio, X_c, in suns [7,44]

$$\beta_{Voc,cell} = \beta_{Voc,cell}(X_c = 1) + (n_{cell}k/q)\ln(X_c) \tag{9}$$

$\beta_{Voc,cell}(X_c=1)$ being the temperature coefficient of V_{oc} for the cell at one sun and n_{cell} the diode ideality factor of the cell.

Based on this equation, it can be assumed that the temperature coefficient for an HCPV module could be approximated by

$$\beta_{Voc} \approx \beta_{Voc0} + N_s(nk/q)\ln(DNI/DNI^*) \approx \beta_{Voc0} + N_s(nk/q)\ln(I_{sc}/I_{sc}{}^*) \tag{10}$$

β_{Voc0} being the temperature coefficient of V_{oc} for the module at the defined reference irradiance DNI^*.

Taking this into account, the method is derived from Eq. (6) by neglecting the variations of the thermal voltage term over the range of operation temperatures. This equation can be rewritten as

$$V_{oc} = V_{oc}{}^* + N_s(nkT_{c(K)}{}^*/q)\ln(I_{sc}/I_{sc}{}^*) + \beta_{Voc}(T_{c(K)} - T_{c(K)}{}^*) \tag{11}$$

By replacing Eq. (10) into Eq. (11), an expression for calculating the absolute cell temperature is achieved

$$T_{c(K)} = T_{c(K)}{}^* + \frac{V_{oc} - V_{oc}{}^* - N_s(nkT_{c(K)}{}^*/q)\ln(I_{sc}/I_{sc}{}^*)}{\beta_{Voc0} + N_s(nk/q)\ln(I_{sc}/I_{sc}{}^*)} \tag{12}$$

The method depends on the same parameters than the V_{oc}–I_{sc} method so that it can be used as an alternative that theoretically could improve the estimation. However, it is important to remark that the method was not validated by the authors for HCPV modules operating outdoors, so that the usefulness of the method for the case of HCPV modules is still unknown. Authors evaluated the method for a single cell measured in a solar simulator under different concentration levels ranging from 1 to 1000 suns. From these measurements, the method presented better results than the V_{oc}–I_{sc} method especially at high concentrations.

4.3. Method of Peharz et al. (2011)

The method presented by Peharz et al. [18] from the Fraunhofer Institut für Solare Energiessysteme is based on an indoor characterization procedure applied to several HCPV modules. Different measurements carried out in a sun simulator allowed the authors deriving a functional dependence of the cell temperature from the module electrical parameters of open-circuit voltage and short-circuit current.

The sun simulator used for the study [45] allows controlling the light intensity incident on the module by means of a flash bulb. The module temperature can also be controlled by irradiating the module backside by several infrared light bulbs. This temperature can be varied by changing the distance between the bulbs and the module. After about 30 min of infrared irradiation, the back temperature of the module is stable and can be measured with a thermocouple placed on uniformly spaced points, what allows determining the average temperature across the backside of the module. A theoretical analysis based on Fourier's heat conduction equation showed that this average temperature is almost the same than the cell temperature at the described thermal equilibrium condition (with a difference less than 0.1 °C). Thus, the cell temperature can be controlled in the simulator and can be determined from the measurements of the thermocouple.

With this experimental set-up, the V_{oc} and I_{sc} of the modules under study were systematically measured at different conditions of irradiance and temperature. It was found that the open-circuit voltage fitted the following function:

$$V_{oc} = [a_1\ln(I_{sc}) + a_2] + [b_1\ln(I_{sc}) + b_2]T_c \tag{13}$$

and from this equation, the cell temperature can be expressed as

$$T_c = \frac{V_{oc} - a_1\ln(I_{sc}) - a_2}{b_1\ln(I_{sc}) + b_2} \tag{14}$$

The main difficulty of the method is that a complex experimental set-up is required for obtaining the a_1, a_2, b_1 and b_2 parameters for a particular HCPV module. However, in the present research, we propose an alternative to this procedure based on outdoor measurements. It consists on monitoring the HCPV module during an experimental campaign of several months in order to register measurements of cell temperature, open-circuit voltage and short-circuit current over a representative range of values. From the measurements, a multi-linear regression analysis can be done taking into account Eq. (13) that allows the determination of the four parameters. Results of this outdoor procedure is shown in Section 6.

4.4. Method of Fernández et al. (2013)

The method proposed by Fernández et al. [46] uses linear coefficients in order to express the dependence of open-circuit voltage (V_{oc}) on DNI and cell temperature (T_c)

$$V_{oc} = c_1 DNI + c_2 T_c + c_3 \tag{15}$$

This way, once the coefficients have been determined, the cell temperature is calculated by

$$T_c = (V_{oc} - c_1 DNI - c_3)/c_2 \tag{16}$$

The method is simple but requires an outdoor experimental campaign on a monitored module in order to obtain the coefficients.

4.5. Method of Yandt et al. (2012)

The above methods are intended for calculating the cell temperature in an HCPV module at open-circuit condition. An interesting aspect in HCPV is to investigate the cell temperature of the module working at maximum power point (MPP). At MPP, the module is harvesting electricity and this energy is not transformed to heat. As a result, the cell temperature at MPP ($T_{c,MPP}$) will be lower than the cell temperature as measured at open-circuit ($T_{c,meas}$). Knowing the cell temperature at MPP can be interesting in certain studies, for instance in the energy harvesting calculation of an HCPV system.

Yandt et al. [47] proposed a method for calculating the cell temperature at MPP. It is based on correcting $T_{c,meas}$ in order to estimate $T_{c,MPP}$. The method requires measuring the whole I–V curve of a monitored module and uses the atmospheric conditions of ambient temperature (T_{air}) and DNI.

The absolute thermal resistance (R_{th}) between the solar cell and the ambient is used to derive the method. This magnitude can be defined as

$$R_{th} = (T_c - T_{air}/Q) \tag{17}$$

Q being the rate of heat transfer through conduction and convection. This definition can be applied to both the MPP module and the measured module

$$R_{th} = (T_{c,MPP} - T_{air})/Q_{MPP} = (T_{c,meas} - T_{air})/Q_{meas} \tag{18}$$

$$R_{th} = \Delta T_{MPP}/Q_{MPP} = \Delta T_{meas}/Q_{meas} \tag{19}$$

The Q_{MPP} and Q_{meas} rates can be expressed as the difference between the luminous power absorbed by the cells in the module (P_{abs}) and the electrical power harvested by the module

$$Q_{MPP} = P_{abs} - P_{MPP}(T_{c,MPP}) \tag{20}$$

$$Q_{meas} = P_{abs} - P_{meas,AVG}(T_{c,meas}) \tag{21}$$

where $P_{MPP}(T_{c,MPP})$ is the power of the MPP module operating at $T_{c,MPP}$ temperature and $P_{meas,AVG}(T_{c,meas})$ is the averaged power harvested by the measured module during testing (while performing the voltage sweep needed to trace the I–V curve) at $T_{c,meas}$ temperature. The averaged power harvested by the measured module can be calculated from the registered P–V curve:

$$P_{meas,AVG} = (1/V_{oc}) \int_0^{Voc} P(V)dV \tag{22}$$

Thus, from Eq. (19) the following can be written:

$$\frac{\Delta T_{MPP}}{1 - P_{MPP}(T_{c,MPP})/P_{abs}} = \frac{\Delta T_{meas}}{1 - P_{meas,AVG}(T_{c,meas})/P_{abs}} \tag{23}$$

$$\Delta T_{MPP} = \Delta T_{meas} \frac{1 - \eta_{MPP}(T_{c,MPP})}{1 - \eta_{meas}(T_{c,meas})} \tag{24}$$

η_{MPP}, η_{meas} being the efficiencies related to the luminous power absorbed by the cells for the cases of the MPP module and the measured module respectively.

In Eq. (24), $\eta_{MPP}(T_{c,MPP})$ is unknown. However, a first approach to this value is $\eta_{MPP}(T_{c,meas})$, which can be extracted from the maximum power of the measured I–V curve. Taking this into account, the authors propose an iterative method for calculating ΔT_{MPP}. It is based on the following sequence:

$$\Delta T_{MPP(n)} = \Delta T_{meas} \frac{1 - \eta_{MPP}(T_{c,MPP(n-1)})}{1 - \eta_{meas}(T_{c,meas})} \tag{25}$$

where $T_{c,MPP(0)} = T_{c,meas}$ and $\Delta T_{MPP} = \Delta T_{MPP}(\infty)$.

One of the difficulties of the method is that the luminous power absorbed by the cells is not easily obtainable. A first approach to this power could be

$$P_{abs} \approx \eta_{opt} DNI A_{mod} \tag{26}$$

η_{opt} being the module optical efficiency and A_{mod} the module aperture area. However, not all of this quantity is actually absorbed by the cell because some light is reflected and some light is transmitted [48–50]. Also, as it is known, η_{opt} depends on factors such as incident spectrum and lens temperature, so that establishing a constant value for the optical efficiency would be only an approximation [51–53].

It is remarkable that the authors of the method have not yet published experimental validation, i.e. results of the method compared against measured cell temperatures at MPP have not yet been reported.

5. Methods based on atmospheric parameters

The methods reviewed above require some direct measurements on a module so that they are adequate during field performance studies. However, when the set-up needed for the measurements is not available or when dealing with studies based on typical meteorological data, that practice is not possible. In these cases, methods only based on atmospheric parameters must be used for estimating the cell temperature.

An important task for the analysis of an HCPV installation is to estimate the energy harvesting. This is done from values of several atmospheric parameters, such as DNI, ambient temperature or wind speed, among others. As the cell temperature is an important factor for energy harvesting calculations, it is very interesting to have methods that exclusively estimate this temperature from atmospheric parameters. These procedures present uncertainties related to the sources of the meteorological data and related to the model itself but have proven to be a very useful tool [54].

5.1. Method of Almonacid et al. (2012)

The method presented by Almonacid et al. [13] uses linear coefficients in order to estimate the cell temperature in an HCPV module from ambient temperature (T_{air}), *DNI* and wind speed (*WS*). It is based on the following relation:

$$T_c = T_{air} + d_1 DNI + d_2 WS \tag{27}$$

where d_1 and d_2 parameters must be obtained by means of multi-linear regression analysis of monitored data for the analyzed HCPV module.

5.2. Method of Hornung et al. (2012)

A slightly more sophisticated method was proposed by Hornung et al. [55] based on the same atmospheric parameters than the previous one. In this case, the cell temperature is estimated by

$$T_c = T_{air} + m[\exp(-0.5WS/WS_0) + c]DNI \tag{28}$$

The method assumes the temperature gap between the cell and the ambient to be proportional to the *DNI*, with an exponential correction based on wind speed. A multi-linear regression analysis can be done to obtain the model coefficients from monitored data.

5.3. Method of Fernández et al. based on ANN (2013)

The above two methods use simple algebraic functions for characterizing the relation between cell temperature and atmospheric parameters. Actually, this relation is more complex. Because of this, Fernández et al. [40] tried to characterize this relation by using an artificial neural network (ANN) in order to find a more accurate model. ANNs have proven to be very useful for solving complex problems and have been recently applied in the HCPV field [56,57].

The same atmospheric parameters than the previous methods are proposed to characterize the cell temperature, i.e. the objective is to find the function

$$T_c = f(T_{air}, DNI, WS) \tag{29}$$

To find this function, a feed-forward ANN composed of three layers was implemented: a three nodes layer (T_{air}, *DNI* and *WS*) as input layer, a five nodes layer as hidden layer and a single node layer (T_c) as output layer. The number of nodes of the hidden layer was empirically determined. This architecture was trained with the Levenberg–Marquardt back-propagation algorithm, which allows determining the coefficients of the ANN (weights and biases of the hidden and output layers). In order to train, validate and test the ANN, a set of outdoor measurements including the cell temperature and the atmospheric parameters must be available for a wide range of operating conditions.

The main difficulty of the method is that an advanced knowledge on ANNs is required to train the network. However, once the coefficients of the network are determined, the method becomes easy-to-use.

After completing the review of existing methods for the calculation of cell temperature in an HCVP module, it is important to remark that some efforts have been made in order to be able to estimate the module heat-sink temperature from atmospheric parameters. These methods can also be useful when the direct measurement of this temperature on the module is not possible. The application of these methods allows converting the methods based on module heat-sink temperature (Section 3) to methods only based on atmospheric parameters. Two proposed expressions are:

– From photovoltaics for utility scale applications (PVUSA) [58]

$$T_{h-s} = A_1 T_{air} + A_2 DNI + A_3 WS \tag{30}$$

Table 1
Summary of characteristics of the methods for calculating the cell temperature in an HCPV module: required inputs, advantages and technical difficulties.

	Methods based on module heat-sink temperature			Methods based on electrical parameters					Methods based on atmospheric parameters		
	Sandia	ISFOC/IES-UPM	Muller	IEC 60904-5	Ju	Peharz	Fernández	Yandt	Almonacid	Hornung	Fernández ANN
Required inputs											
Module heat-sink temperature	√	√	√								
Direct normal irradiance	√	√		√			√	√	√	√	√
Open-circuit voltage			√	√	√	√	√				
Short-circuit current					√	√					
Cell temperature at open-circuit								√			
Whole *I–V* curve								√			
Ambient temperature								√	√	√	√
Wind speed									√	√	√
Advantages											
Outdoor validation has been reported	√	√		√		√	√		√	√	√
Parameters can be obtained from manufacturers or from the literature		√	√	√	√			√			
Does not require direct measurements on the module									√	√	√
Intended for calculating cell temperature at MPP								√			
Technical difficulties											
Requires module with cell temperature sensor to be measured outdoors for determining the parameters	√						√		√	√	√
Requires a sun simulator for determining the parameters						√[a]					
Requires a system that shutters sunlight			√								
Requires the whole *I–V* curve of the module								√			
Requires advanced knowledge on ANN											√

[a] Alternatively, parameters can be determined from outdoor measurements on a module with cell temperature sensor.

– From Sandia National Laboratories [38]

$$T_{h-s} = T_{air} + \exp(B_1 + B_2 WS) DNI. \tag{31}$$

6. Comparative analysis

Table 1 summarizes the required inputs, advantages and technical difficulties of the reviewed methods for calculating the cell temperature in an HCPV module. As can be seen, methods based on direct measurements on the module are preferable for field performance analysis while methods based on atmospheric parameters are suitable when direct measurements on the module are not possible.

Among the methods based on direct measurements, some of them have the advantage that the parameters can be obtained from manufacturer's data or from the scientific literature (ISOFC/IES-UPM, Muller, IEC 60904-5, Ju and Yandt). However, as has been commented, accurate values of the parameters are required because these methods are very sensitive to the chosen values. The rest of the methods based on direct measurements have the difficulty that parameters must be fitted from an outdoor experimental campaign or from indoor measurements in a sun simulator.

Methods based on atmospheric parameters always require an outdoor experimental campaign in order to obtain the parameters and use values of direct normal irradiance, ambient temperature and wind speed as inputs.

The table remarks some technical difficulties related to the application of the methods. As has been commented, some methods require an outdoor experimental campaign on a module with a cell temperature sensor in order to determine the parameters. This kind of device is not often available and the procedure takes time to carry out the measurements. Other technical difficulties are the need of a sun simulator (Peharz), a system that shutters sunlight (Muller), the need of the whole *I–V* curve of the module (Yandt) or the need of advanced knowledge in ANN (Fernández ANN).

As can be seen in the table, only one method is intended for calculating the cell temperature of a module operating at maximum power point (Yandt). Authors of this method predicted a difference of up to 14 °C between the cell temperature at open-circuit and the cell temperature at MPP [47]. Thus, investigating the cell temperature at MPP is interesting in HCPV and further research in this field is expected. In addition, it is important to remark that there are three methods whose outdoor validation against measured cell temperature has not yet been reported (Muller, Ju and Yandt).

A quantitative comparison of the methods has also been carried out. For this purpose, an HCPV module equipped with cell temperature sensor and heat-sink temperature sensor was measured for two years, from January 2011 to December 2012, at Jaén, South of Spain. The temperatures were recorded every 5 min together with the main atmospheric parameters (direct normal irradiance, ambient temperature and wind speed). Also, an *I–V* tracer simultaneously measured the module *I–V* curve, from which the electrical parameters open-circuit voltage and short-circuit current can be extracted. The main characteristics of the measured module are depicted in Table 2.

In order to carry out the experimental campaign, the module was mounted on a two-axis solar tracker located at the Centro de Estudios Avanzados en Energía y Medio Ambiente (CEAEMA) of Jaén University. Jaén climate is characterized by a high level of annual direct normal irradiation and ambient temperatures that can easily reach 40 °C in summer and 5 °C in winter [59]. In these climatic conditions, a wide range of cell operating temperatures was registered during the experiment, what allows guaranteeing the confidence of the procedure used for evaluating the accuracy of the different methods. Fig. 5 shows the histogram of measured cell temperatures during the two-years campaign.

From the collected data, the parameters of the different methods were determined. Each method was implemented and the root mean square error (RMSE) in °C between calculated and measured cell temperature was obtained by

$$\text{RMSE}\ (^{\circ}\text{C}) = \sqrt{(1/N)\sum_{i=1}^{N}\left(T_{c,calculated} - T_{c,measured}\right)^2} \tag{32}$$

The procedure was only applied to methods whose outdoor validation has been reported. Results are shown in Table 3.

As can be seen, methods based on direct measurements on the module (RMSEs from 1.7 to 2.5 °C) are more accurate than methods only based on atmospheric parameters (RMSEs from 3.2 to 4.3 °C) as expected. Among the methods based on direct measurements, methods based on module heat-sink temperature (RMSEs from 1.7 to 2.2 °C) have the same order of error magnitude than methods based on electrical parameters (RMSEs from 1.8 to 2.5 °C).

Regarding methods based on module heat-sink temperature, the method of ISFOC/IES-UPM gave lower error than the method of Sandia (1.7 °C vs. 2.2 °C). This is probably because a detailed knowledge of the materials between the cell and the heat-sink was available in order to determine the “internal thermal resistance” parameter (ρ) of the ISFOC/IES-UPM method, while the ΔT parameter of the Sandia method was determined from an average of the measurements taken around the reference irradiance.

Regarding methods based on electrical parameters, the best behavior was observed for the method of Peharz (RMSE = 1.8 °C). This can be due to the fact that the functional dependence of the cell temperature on electrical parameters was carefully obtained by the authors through indoor measurements in a sun simulator.

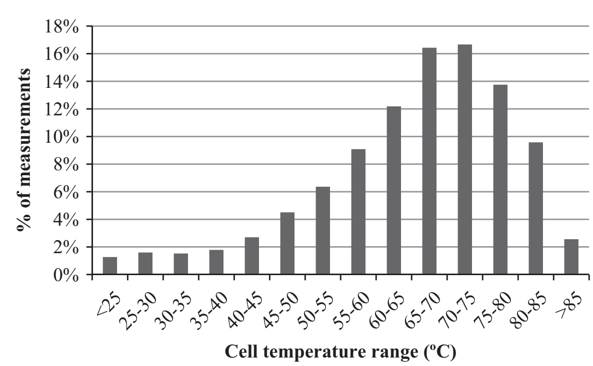

Fig. 5. Histogram of measured cell temperatures during the experimental campaign.

Table 2
Characteristics of the measured HCPV module.

Geometric concentration	Primary optics	Secondary optics	Type of solar cells	Number of solar cells	Cooling
500 ×	PMMA squared flat Fresnel lens	Refractive truncated pyramid	Lattice-matched GaInP/GaInAs/Ge	6 Cells in series	Passive

Table 3
Errors between predicted and measured cell temperature for different methods.

	RMSE (°C)
Methods based on module heat-sink temperature	
Sandia	2.2
ISFOC/IES-UPM	1.7
Methods based on electrical parameters	
IEC 60904-5	2.0
Peharz	1.8
Fernández	2.5
Methods based on atmospheric parameters	
Almonacid	4.3
Hornung	4.0
Fernández ANN	3.2

Method of IEC 60904-5, which is based on physical parameters, also gave good results (RMSE = 2.0 °C). Method of Fernández performed slightly worse (RMSE = 2.5 °C), but has the advantage that it is based on a simple linear expression.

Regarding methods based on atmospheric parameters, the method of Almonacid, which is based on linear coefficients, has the highest RMSE (4.3 °C). The method of Hornung performed slightly better (RMSE = 4.0 °C) probably because it introduces an exponential correction based on wind speed. The best of these methods is the ANN-based method (RMSE = 3.2 °C), which is able to better characterize the complex relation between cell temperature and atmospheric parameters.

7. Conclusions

A review of existing methods for cell temperature calculation in HCPV modules for electrical characterization has been done. Methods have been classified into methods based on direct measurements on the module and methods based on atmospheric parameters. Methods based on direct measurements are preferable during field performance analysis while methods based on atmospheric parameters are interesting when direct measurements on the module are not possible. In turn, methods based on direct measurements have been classified into methods based on module heat-sink temperature and methods based on electrical parameters.

Five of the reviewed methods present the advantage that their parameters can be obtained from manufacturers' data or from the literature (ISOFC/IES-UPM, Muller, IEC 60904-5, Ju and Yandt), what makes easier their application. The rest of the methods require an outdoor experimental campaign in order to determine the parameters or measurements in a sun simulator, what makes more difficult their application. We have also identified other technical difficulties related to the application of some methods, such as the need of a system that shutters sunlight (Muller), the need of the whole *I–V* curve of the module (Yandt) or the need of advanced knowledge in ANN (Fernández ANN).

One of the methods is intended for calculating cell temperature of the module working at MPP (Yandt). Its authors predicted a difference of up to 14 °C between cell temperature at open-circuit and cell temperature at MPP. Thus, investigating the cell temperature at MPP could be useful for certain studies and could be interesting in future research works.

A comparative analysis of the methods has been presented. For this purpose, monitored data obtained during an experimental campaign carried out at Jaén, South of Spain, on an HCPV module has been used. Results show that the accuracy of methods based on direct measurements (RMSEs from 1.7 to 2.5 °C) is somewhat better than that of methods based on atmospheric parameters (RMSEs from 3.2 to 4.3 °C). However, it is remarkable that the differences are not very large, i.e. methods based on atmospheric parameters are a useful tool when direct measurements on the module are not possible.

In the context of module power calculations, the obtained errors for all methods are acceptable. As it is shown in Ref. [40], if we take into account the less accurate method (the Almonacid's atmospheric method based on linear coefficients, with a RMSE of 4.3 °C), the error induced by the cell temperature estimation in the calculated power is within ±1.5% of the real power in 88% of the measurements carried out during an experimental campaign of two years at Jaén. This means that the less accurate method can be used to estimate module power accurately enough.

However, depending on the specific application, some methods can be more suitable than others. The choice of the most suitable method is not trivial and will mainly depend on the availability of module information, on the required accuracy and on technical issues.

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